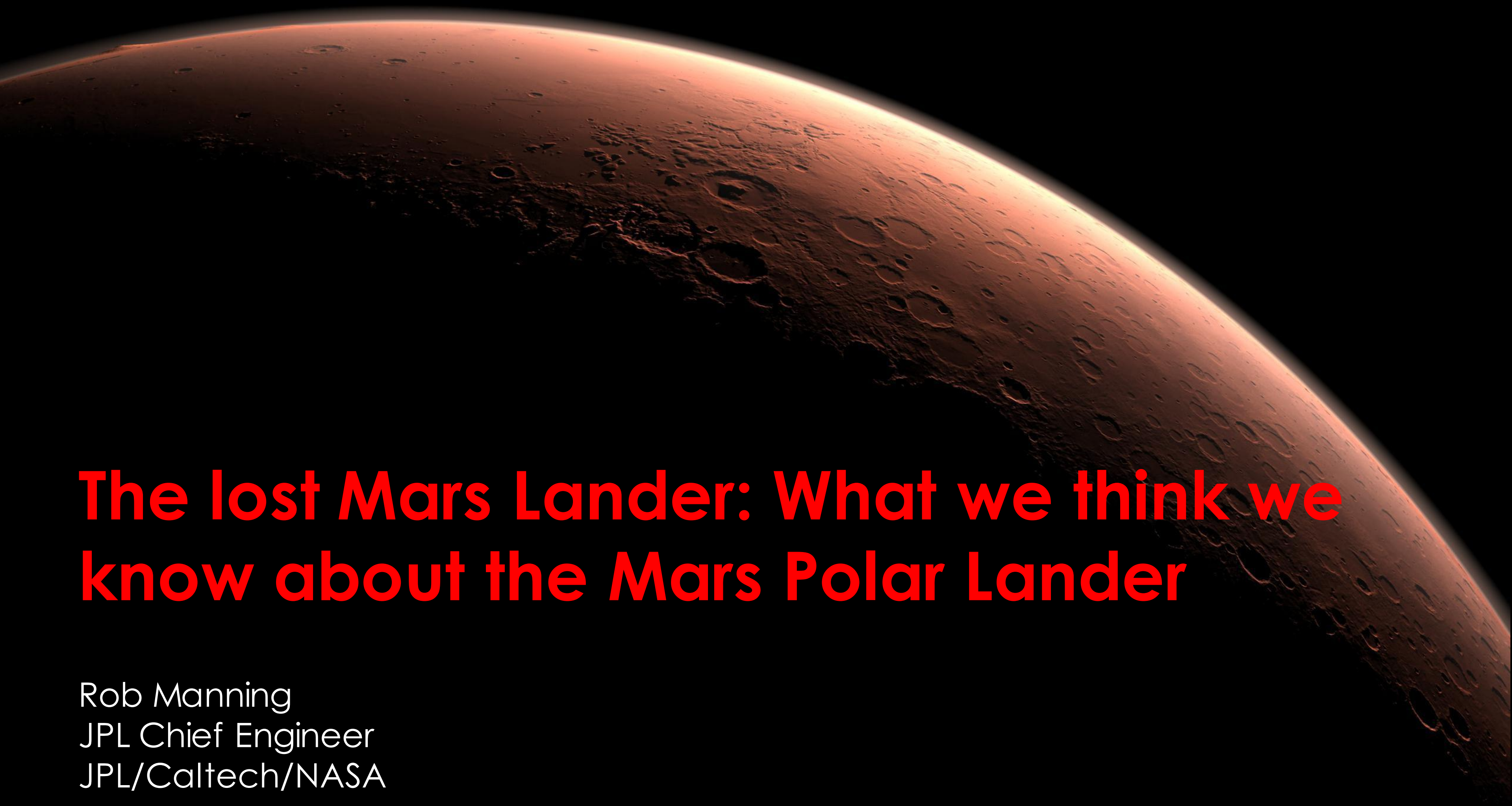
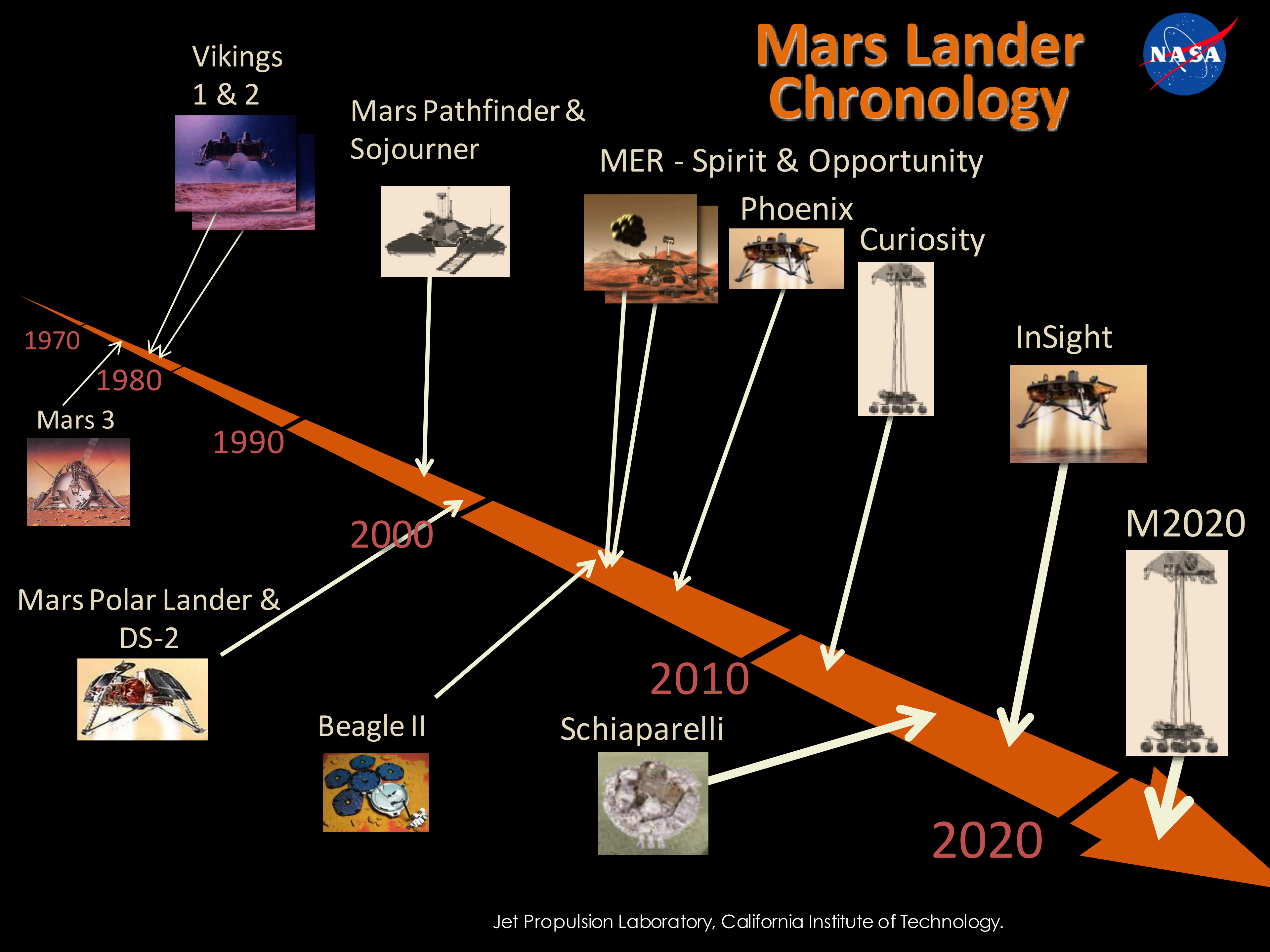


The lost Mars Lander: What we think we know about the Mars Polar Lander

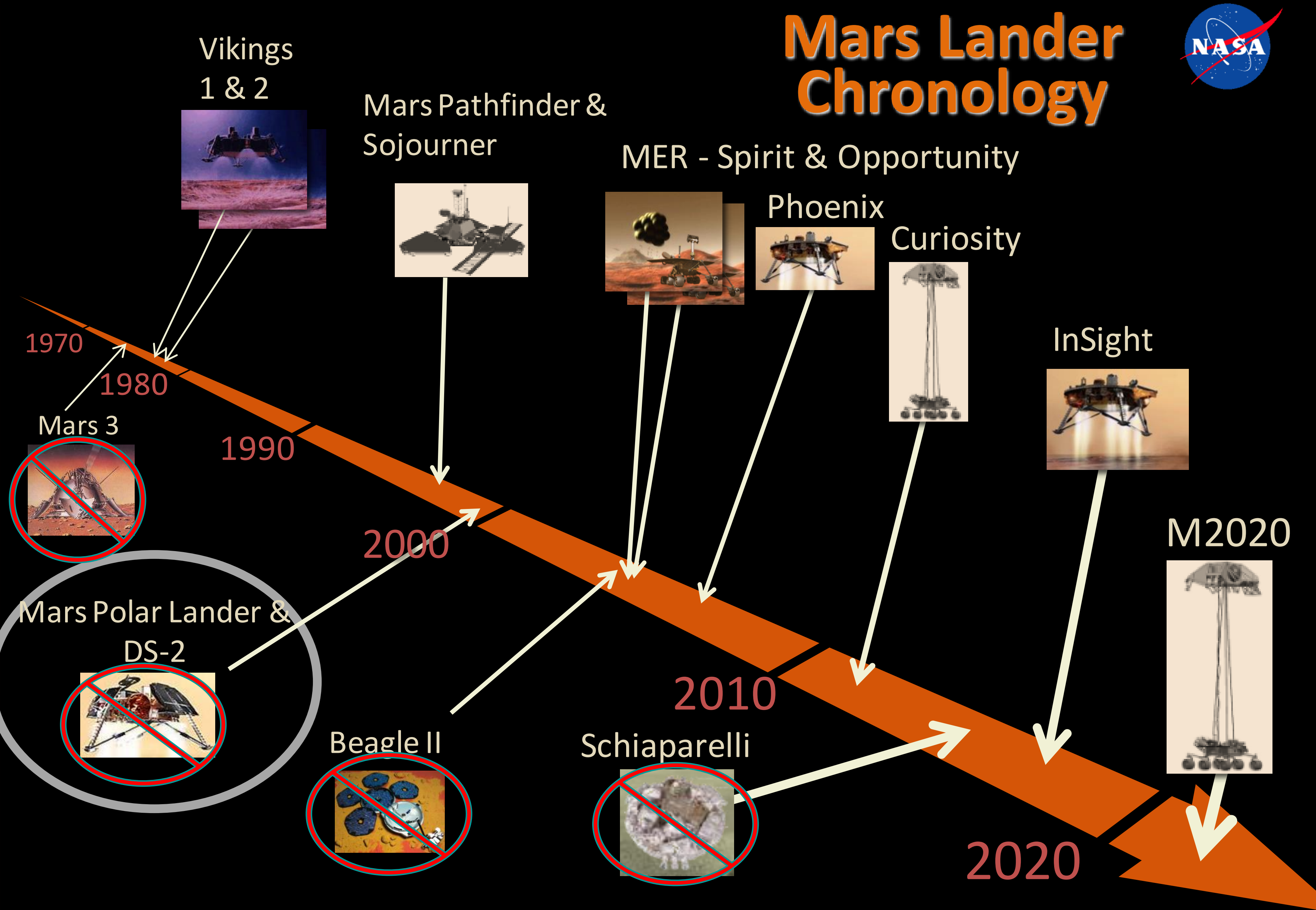
Rob Manning
JPL Chief Engineer
JPL/Caltech/NASA

March 4, 2018
IEEE Aerospace Conference

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology


Mars Lander Chronology
NASA
Vikings 1 & 2
Mars Pathfinder & Sojourner
MER - Spirit & Opportunity
Phoenix
Curiosity
InSight
M2020
1970
1980
1990
2000
2010
2020
Mars 3
Mars Polar Lander & DS-2
Beagle II
Schiaparelli
Jet Propulsion Laboratory, California Institute of Technology.

Mars Lander Chronology



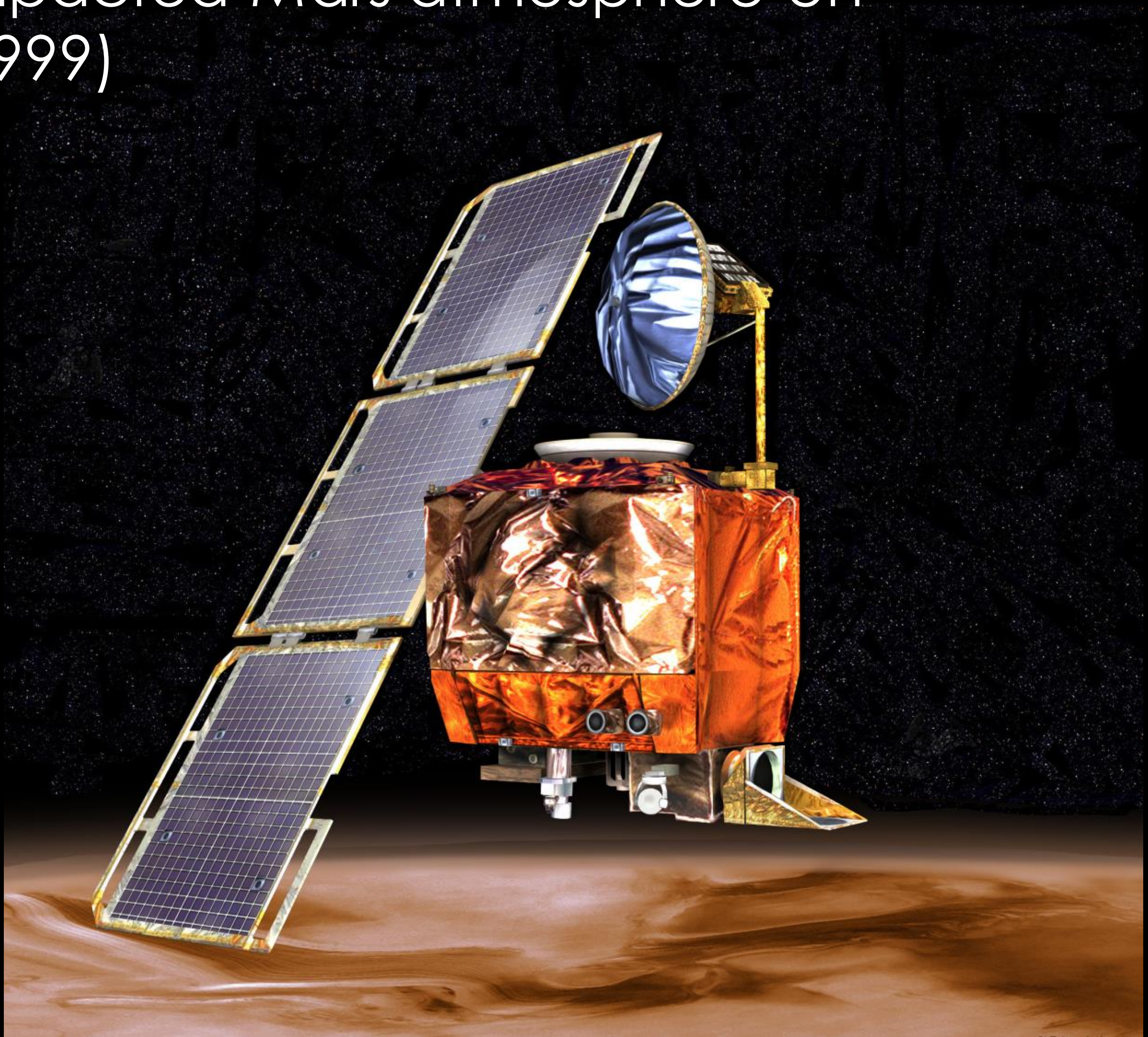
Jet Propulsion Laboratory, California Institute of Technology.

Mars Surveyor Program ’98

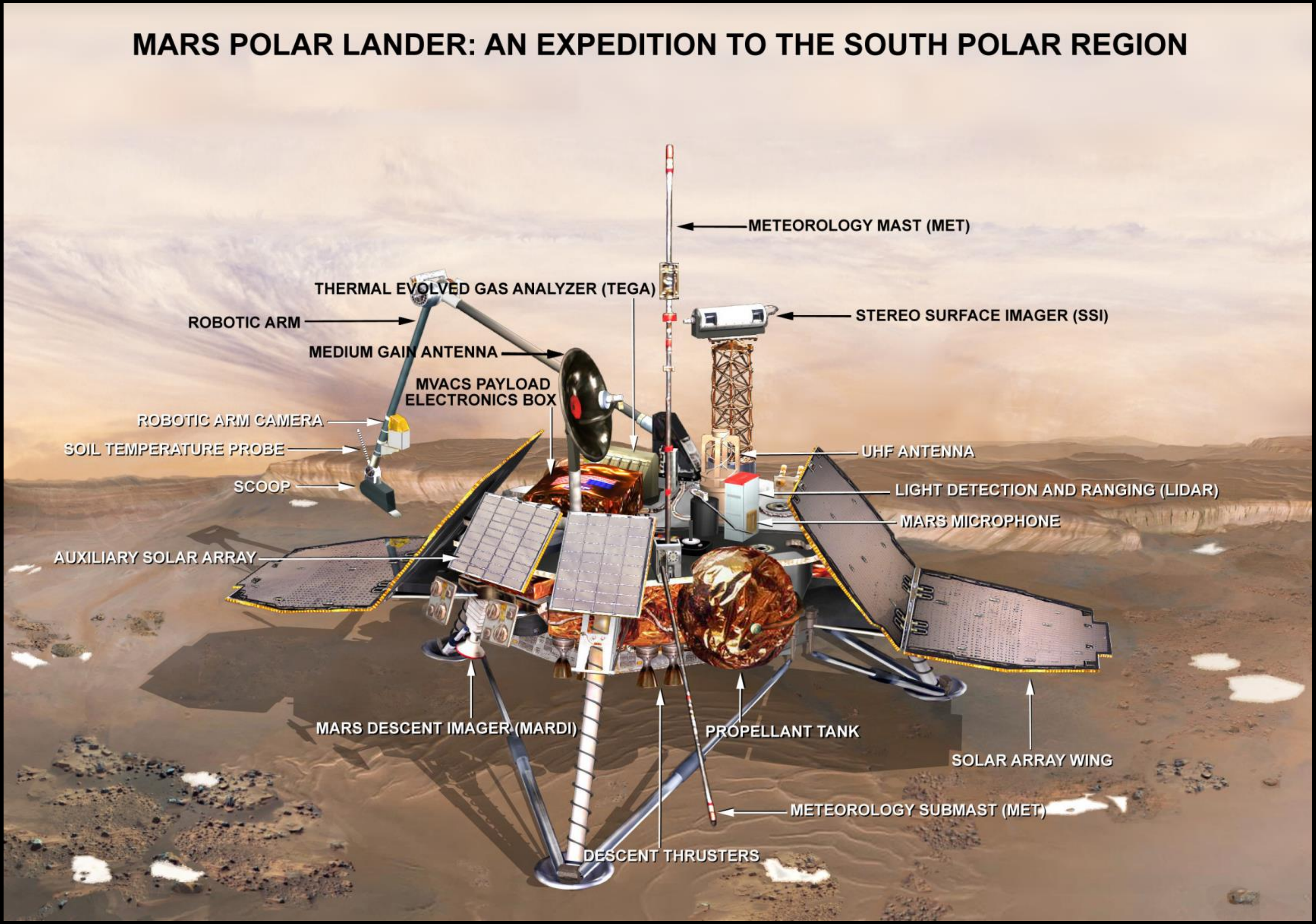
- MSP’98 consisted of a small orbiter and a small low cost Viking-style lander designed and built together but launched separately.
  - The first of a regular drum beat of Mars missions launched in every opportunity.
- Mars Climate Orbiter (MCO)
  - Would replace some of the orbital science lost in the Mars Observer failure in 1996.
- Mars Polar Lander (MPL)
  - Would be the next “normal” lander since Viking.
  - No airbags (Mars Pathfinder had not landed yet!)
  - Instead of expensive throttle valves, it would use 12 pulsed engines to land.
  - One criteria was that no resources would be expended on efforts that did not directly contribute to landing safely on the surface of Mars.
    - On that basis, the it was decided not to provide telemetry during landing.
- Total cost would be $190 M (‘97$)

Mars Climate Orbiter

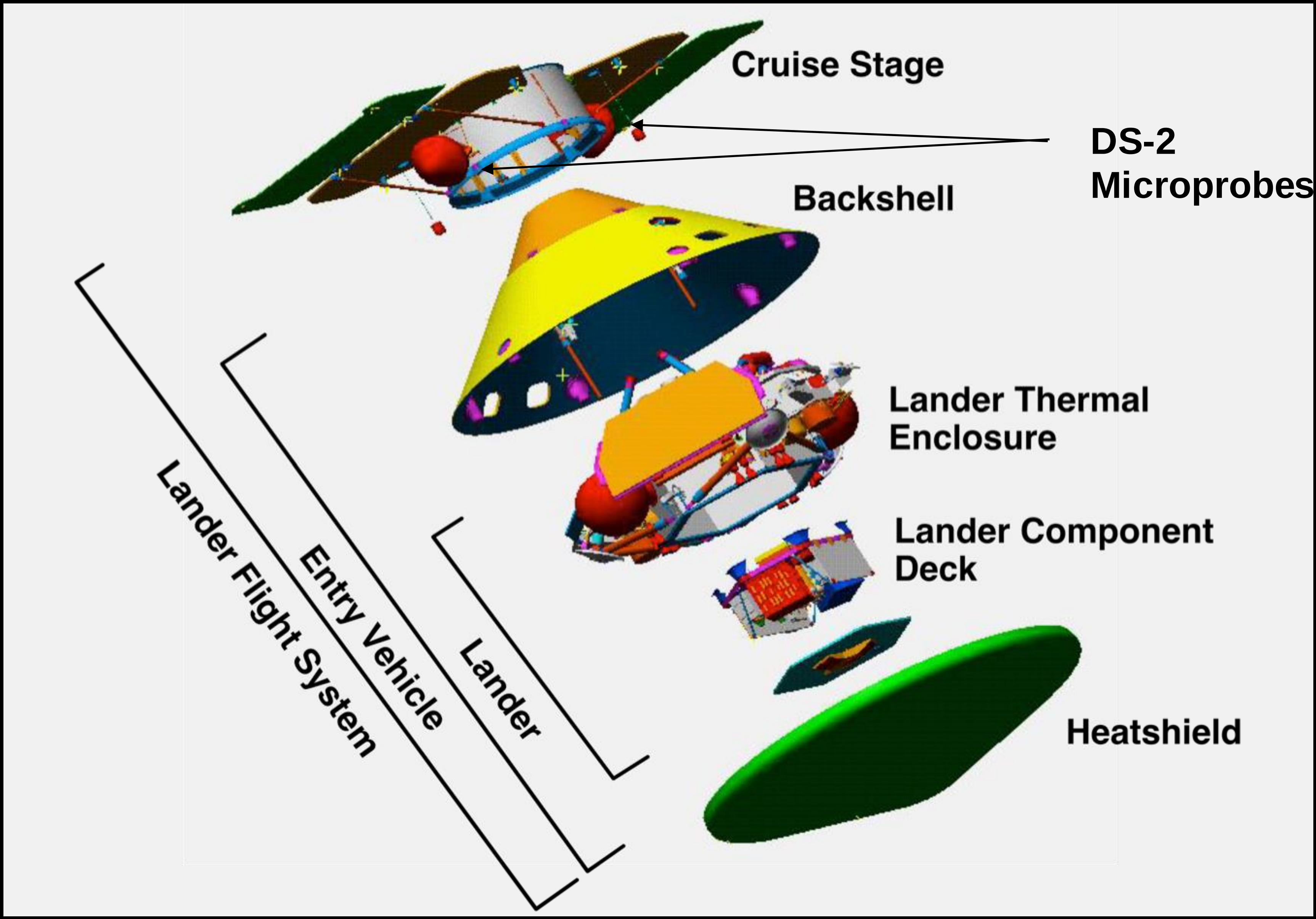
(Inadvertently impacted Mars atmosphere on September 23, 1999)



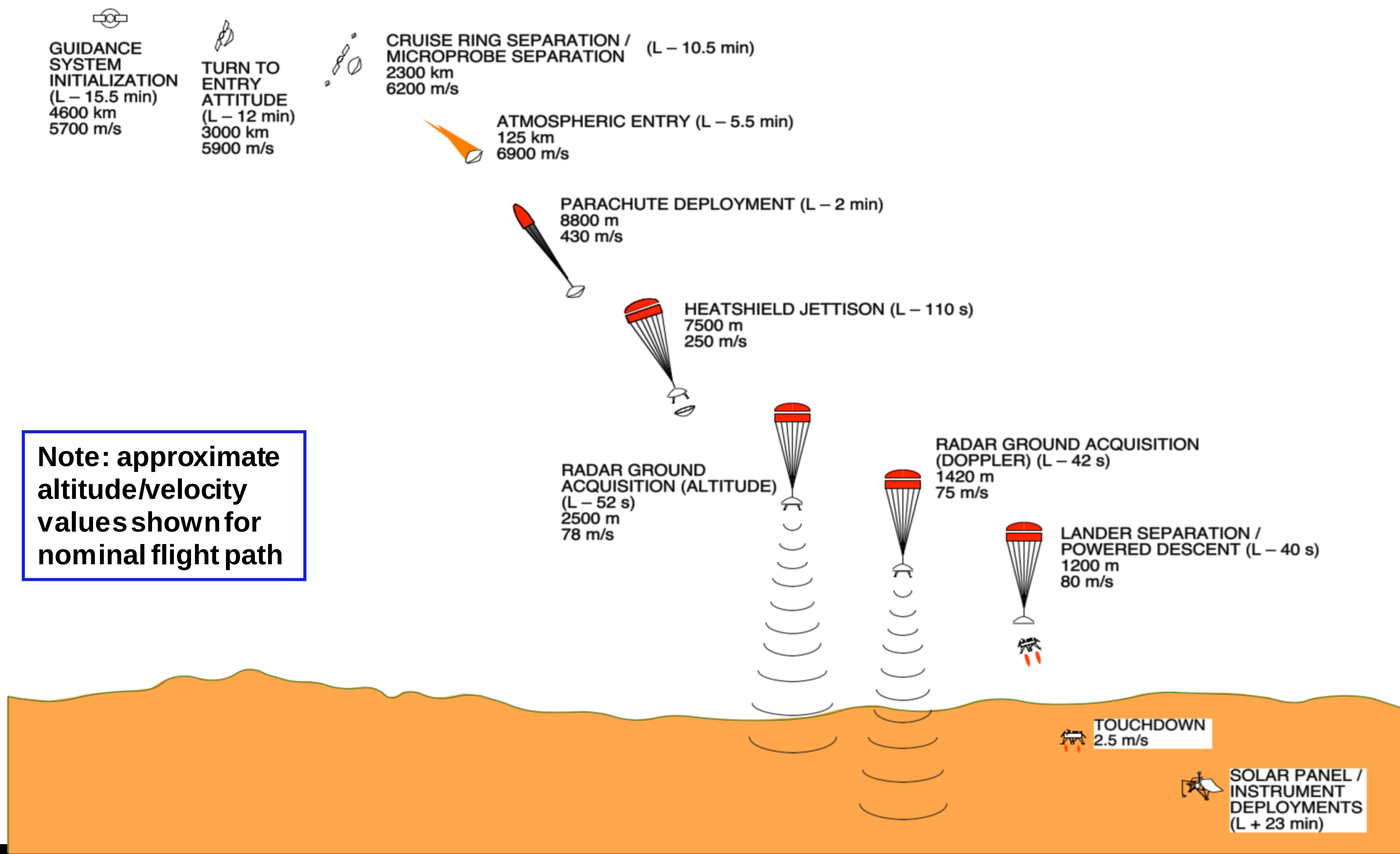
Mars Polar Lander (MPL)



MPL Expanded View



MPL EDL Planned Sequence of Events

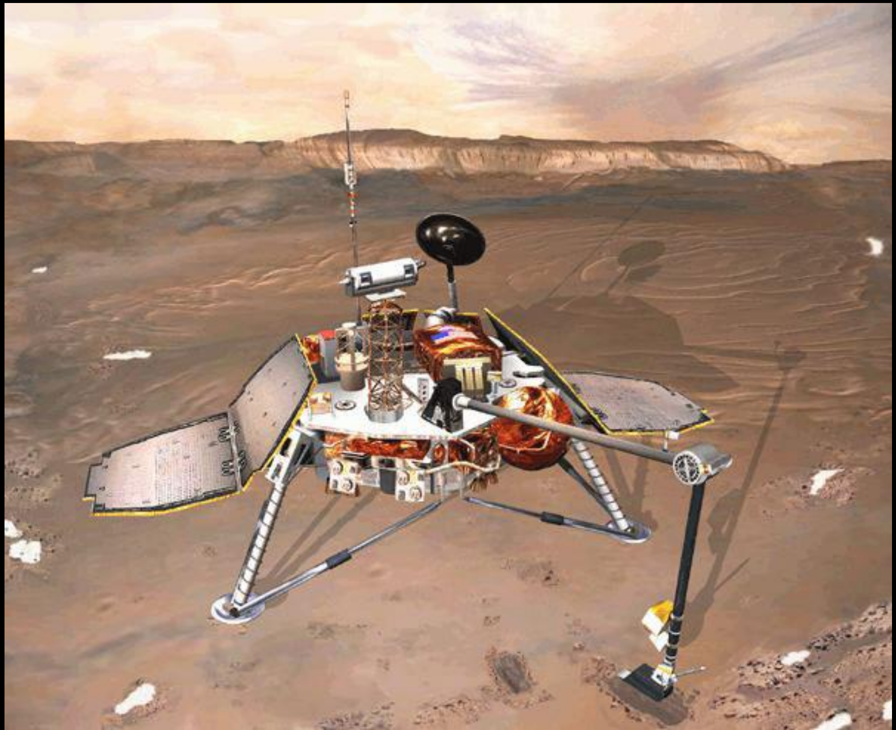


Note: approximate altitude/velocity values shown for nominal flight path

On Dec 3, 1999, less than 3 months after the loss of MCO, MPL arrived and vanished without a traced.

- Just before cruise stage separation, 5 minutes before entry, the radio was turned off as planned.
- The next communication was expected about 30 minutes after landing and solar array deployment

It was never heard from again.



What happened to MPL?

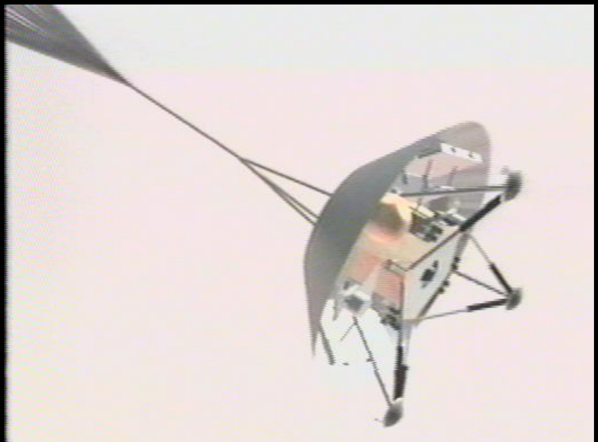
- We don't know.
- The "Report on the Loss of the Mars Polar Lander and Deep Space 2 Missions" 22 March, 2000
  - https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20000061966.pdf
- The report identified key 32 failure modes
  - Of which 7 were deemed "plausible and not unsupported".
  - Another 50 discipline-related failure possibilities were investigated in the report
- In only one of these was there evidence of a genuine candidate root cause.

Official Most Probable Cause

"Premature shutdown of descent engines"

A flight software (FSW) error was discovered 2 months after landing that would have likely have shut down the engines prematurely.

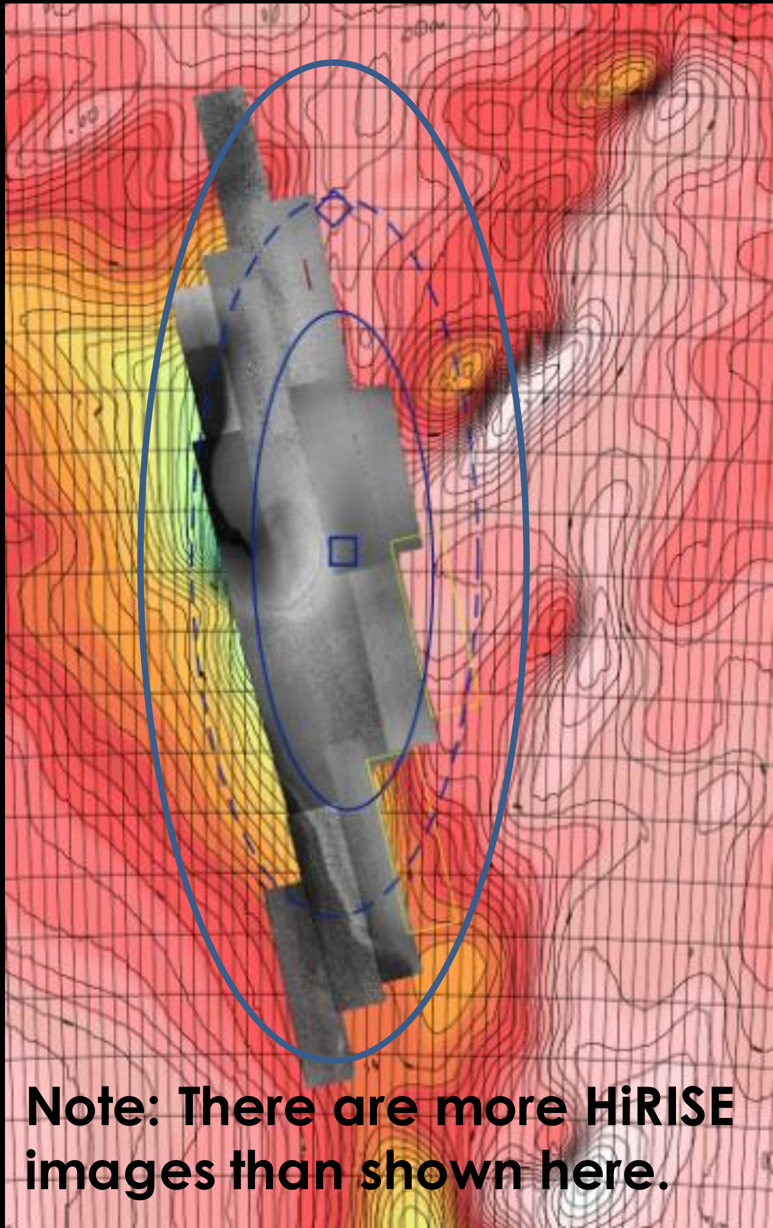
- FSW continuously monitored a Hall effect sensor in each of the legs.
  - If it sees a detection, it makes a note of it
- The sensor pulsed during leg deployment while under the chute. many km above the ground.
- In preparation for landing, at 40 m above the ground engine shutdown was enabled.
- The FSW looked to see if the hall effect sensors had tripped. They had.
- The odds where good that the lander would have fallen 40 m and hit Mars at 50 MPH (22 m/s)



But was that the root cause?

MRO HiRISE Search for MPL

- HiRISE has found Beagle II, cruise stages, rovers, and many more human-made objects on Mars.
- By now, all of the 1-sigma and most of the 2-Sigma (>80%) of the reconstructed MPL landing area has been covered by <1m resolution HiRISE images.
- Not even a glint has been seen.
- We would expected at least a backshell and parachute, if not a lander.
- Where is it?



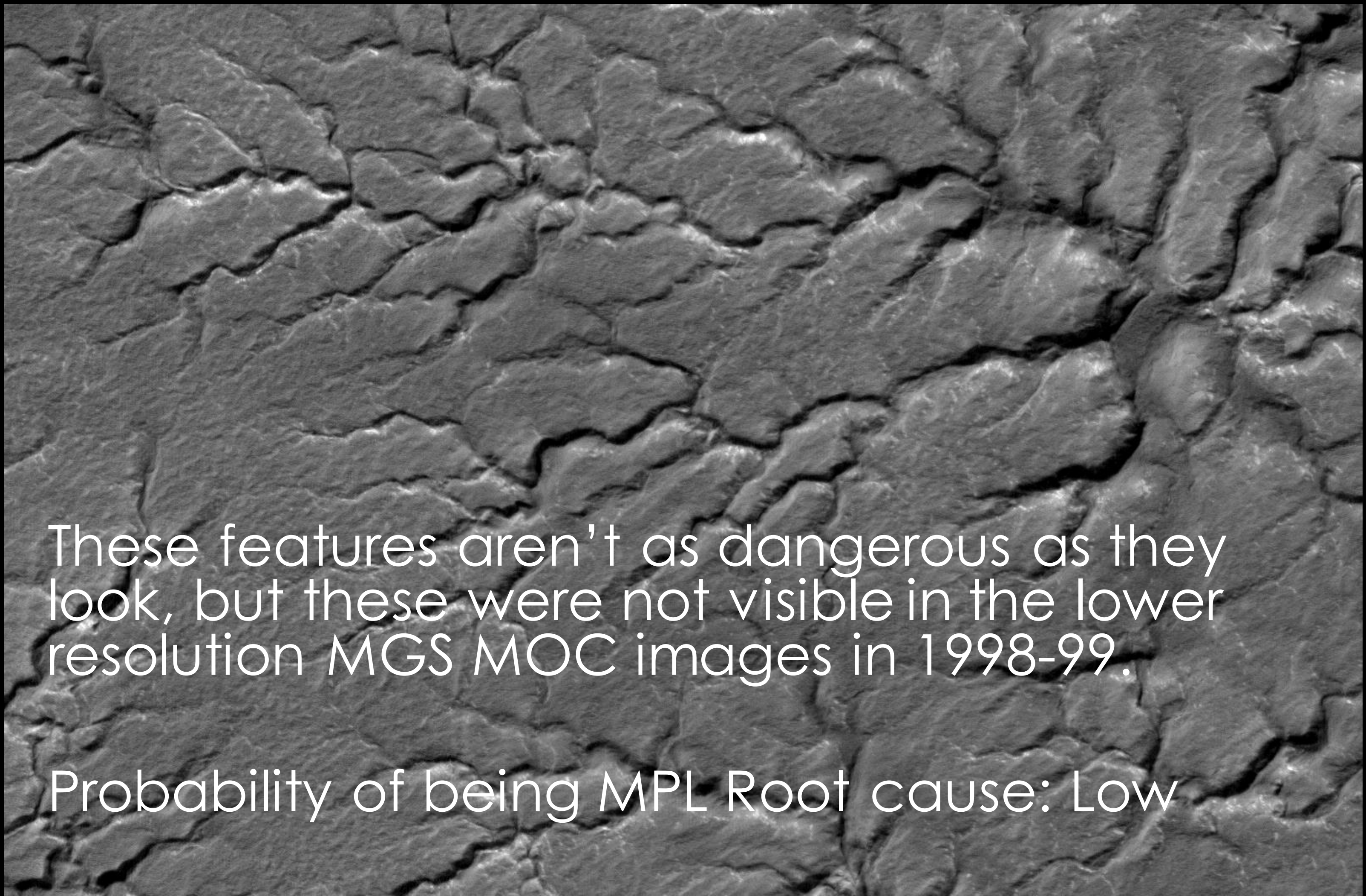
Phoenix development in 2004-2006

- Successfully landed in 2007, the Phoenix (PHX) Lander was built from the mothballed MSP'01 lander.
  - A modified version of MPL

- The Phoenix Project performed a complete reboot of EDL test and analysis program.
  - Added $$ for EDL

- The JPL/LMA/LaRC team discovered and corrected other new root causes that could have also resulted in MPL's demise.

1. Landed in unexpected meter-deep spidery gullies" in ellipse resulting in tip-over.



These features aren't as dangerous as they look, but these were not visible in the lower resolution MGS MOC images in 1998-99.

Probability of being MPL Root cause: Low

2. Command and Data Handling Computer resets due to electronics clocking metastability

- The PHX team discovered a subtle bug in the lander computer's camera interface electronics (FPGA) clocking that would cause it to hang occasionally.
  - This electronics was the interface between the lander computer and the Mars descent imager (MARDI)
- If it occurred, the bug could occasionally result in causing the flight computer to hang and reboot resulting in a crash landing.
- Bug was not fixed on PHX, instead the project elected to forgo descent imaging and imaging science.

Probability of being MPL Root cause: Medium Low

3. Excessive thruster/plume ground pressure torques result in tip over

- Although "Plume ground effects" were noted by the failure review board, the details of what might go wrong was not known.
- CFD analysis by the PHX team revealed that indeed there could be a risk of asymmetric torques on the bottom of the vehicle if the touchdown surface is not flat.
  - The probability of this risk is exacerbated if there is a residual horizontal velocity.
- Given the low horizontal velocity expected at landing, the very fast engine shut down (50 ms) and the relatively low disturbance torque, the PHX project deemed this risk to be low and no additional actions were taken.

Probability of being MPL Root cause: Very Low

4. Simultaneous firing of pyro latch valve could result in low propulsion pressure and insufficient thrust.

- NASA GSFC discovered that if dual pyro valves are fired within (approx.) 10 micro seconds of each other, the pyro might not fire and the valve will not open.
- If the propulsion lines are not opened there may be insufficient pressure to be able to fly to the surface in the using propulsion blow-down system.

Probability of being MPL Root cause: Very Low

5. Bright radar return from the surface could result in excess horizontal velocity errors causing tip-over

- The lander used multiple side-looking (off-nadir) radar beams to estimate horizontal velocity during descent.
  - This works well if the beams are narrow and the angle of the beam is known.
  - However the beams were wide enough that a bright surface could cause the bulk of the radar echo to return from below the lander instead of from the sides.
- These echoes from the surface could “contaminate” the Doppler velocimetry causing large errors in the lander’s estimate of its horizontal velocity causing it to land with high horizontal velocity.
- The PHX project worked to tune how the FSW used the radar to reduce the probability that these errors would be ingested into the navigation filter.

Probability of being MPL Root cause: Low

6. Heat-shield-induced radar range ambiguity causing premature lander separation and eventual crash

- The radar used on MPL was a radar designed for military aircraft.
  - It was not designed to fly in from outer space, drop heatshield in front of it and be expected to operate properly.
- A very subtle spoofing of the radar's internal range ambiguity resolution algorithm by the presence of the falling heatshield was detected by detailed simulation of the radar.
  - As the radar initializes itself on power up, it needs to decide how frequently it should send its radar echoes.
  - More than one echo would confuse the radar. To prevent more than one pulse "in the air" at a time, it sends out a pulse and waits for it to return and then uses that duration to select the repetition frequency.
  - If this pulse bounces off the heatshield, the radar would use that distance to select the frequency.
  - Once the heatshield fell away, the radar would continue with the same pulse rate, but that results in 2 pulses in the air instead of one.

6 cont. Heat-shield-induced radar range ambiguity causing premature lander separation and eventual crash.

- With two pulses in the air instead of one, the radar would think it was only half as high as it really was.
  - Instead of separating at 1.2 km, the lander would separate from the backshell at 2.4 km (8000 ft).
- Like Schiaparelli lander, there was not enough fuel to descend to the surface from that altitude. The lander would have crashed.
- The PHX team tuned the Phoenix FSW so that the radar was initialized after the heatshield was far enough away to be say.

Probability of being MPL Root cause: Medium high

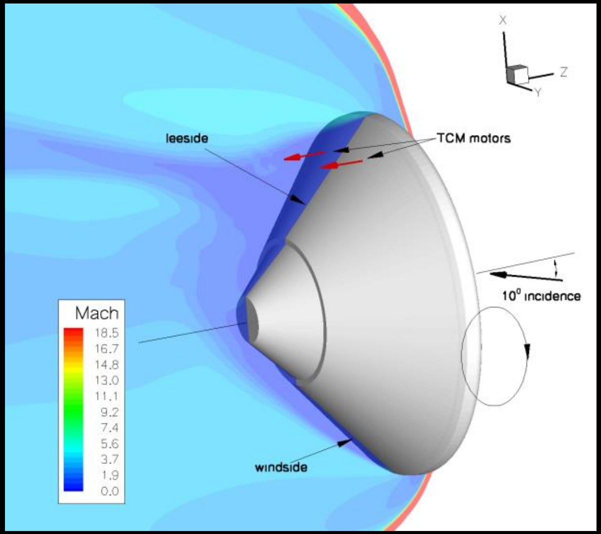
7. Hang up of the RCS motor seal could lead to lander-backshell recontact after lander separation.

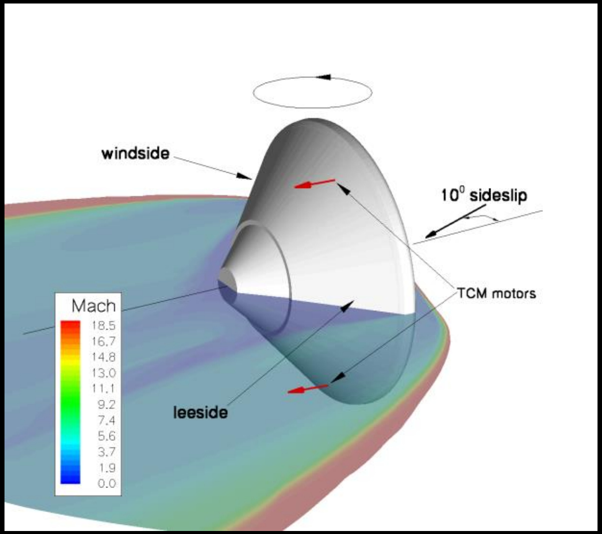
- The reaction control subsystem (RCS) is used during entry for attitude control.
  - These Lander-mounted thrusters penetrate the backshell and are surrounded by thermal seals to keep the heat of entry out.
- During PHX separation testing, it was discovered that the seals could hang up on the lander's RCS thrusters as the lander fell away from the backshell while hanging on the parachute 1.2 km above the ground.
- This would lead to uncertain lander dynamics and damage with unknown but possibly severe consequences.
- The PHX team redesigned the seal to prevent hangup.
-

Probability of being MPL Root cause: Medium

9. RCS-aero thrust reversal could lead to loss of attitude control and tumbling in late entry before parachute deployment

- While performing RCS thruster plume steady state CFD analysis, the PHX team discovered that there could be large uncertainty in both *magnitude and sign* of the induced moments on the yaw RCS thrusters used for 3-axis control during entry.
- Control inversion would have resulted in dynamic instabilities and possibly tumbling.
  - Especially sensitive in the pre-parachute deploy supersonic regime





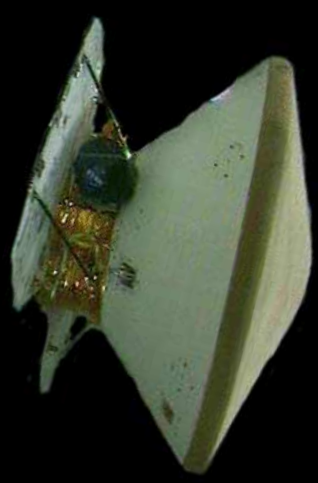
9. Cont. RCS-aero thrust reversal could lead to loss of attitude control and tumbling in late entry before parachute deployment

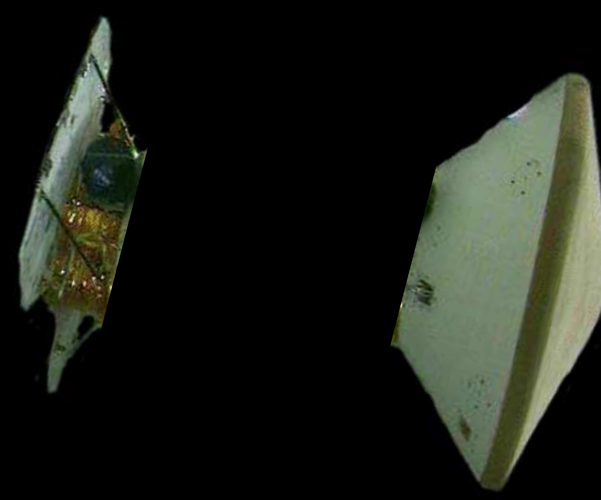
- PHX decided to effectively "turned off" RCS during entry (after using the RCS to perform the turn to the entry attitude).
- It was felt to be safer if the vehicle simply flew into Mars as a passive "knuckle ball".
  - The first ever. (It worked!)
  - Same for InSight.
-

Probability of being MPL Root cause: Medium

10. Cruise stage breakup and recontact with the entry vehicle leads to damage, dynamics and/or destruction

- Cruise stage pushes off springs to separate from entry vehicle (from behind) 5 min before start of entry.
- Initially having lower a ballistic number than the entry vehicle causes it to get further behind the entry vehicle.





10. Cont. Cruise stage breakup and recontact with the entry vehicle leads to damage, dynamics and/or destruction

- New "burn up and breakup codes" developed after the Colombia loss allowed the PHX team to delve into this more deeply.
- The team learned that in 100 s, the cruise stage solar arrays melt off, leaving much higher ballistic coefficient cruise stage hardware to speed up (including the launch vehicle adapter ring).
- These large pieces would "catch up" and pass the entry vehicle less than 6 meters away.
  - Leading components could have impacted HS.

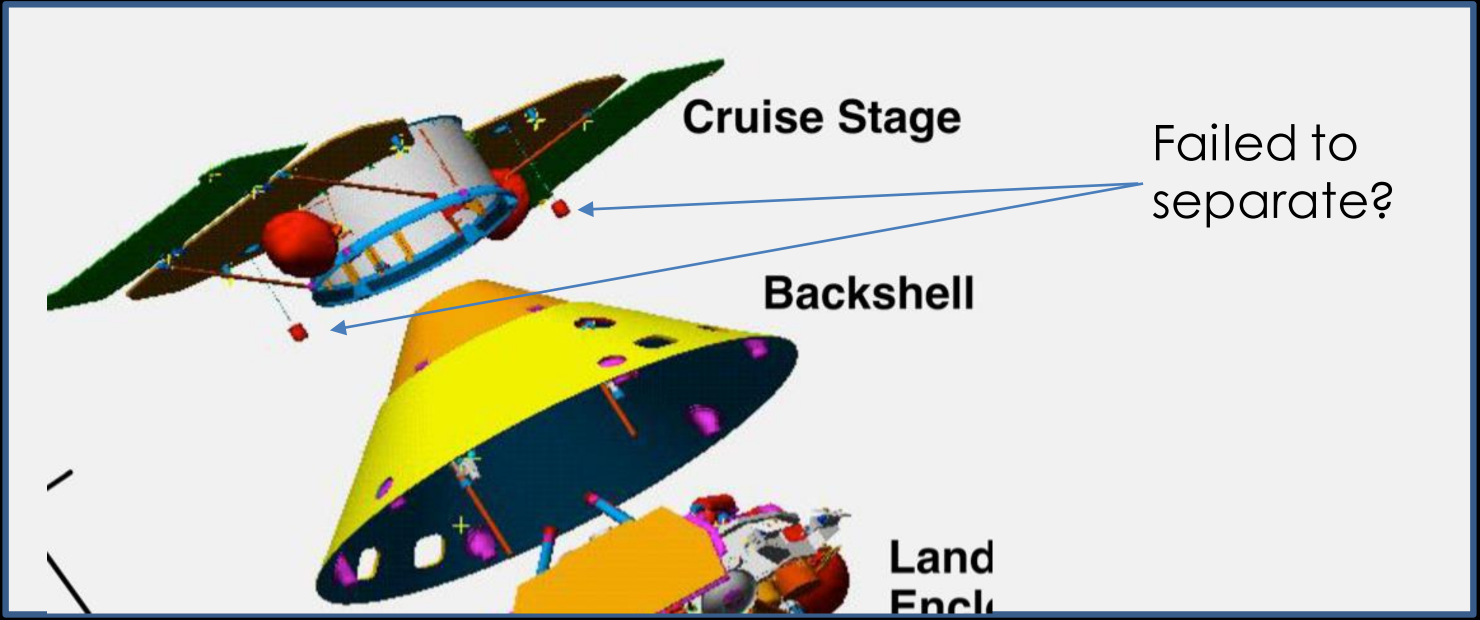
10. Cont. Cruise stage breakup and recontact with the entry vehicle leads to damage, dynamics and/or destruction

- In retrospect we learned that this phenomena would have also threatened Mars Pathfinder and MER (Spirit and Opportunity) during those landings.
- Did we get lucky?
- PHX (& MSL) changed Cruise stage orientation out of plane.
  - Cruise stage allowed to break up off to one side of the entry vehicle's trajectory.

Probability of being MPL Root cause: Medium

11. Cruise stage separation connectors hang leading to tumbling and loss of Vehicle (and the two DS-2 microprobes)

- There were two lanyard-pull electrical separation connectors between the cruise stage and the entry vehicle (on the entry vehicle).



11. Cont. Cruise stage separation connectors hang leading to tumbling and loss of Vehicle (and the two DS-2 microprobes)

- Pull testing at the flight temperature of -75C required more than 100 lb of force. PHX discovered that these connectors were not designed to separate at -75 C.
- This would have led to complex multibody dynamics and uncertain aerodynamics and excessive aeroheating and possible breakup.
  - Connectors may have eventually released due to backshell heating.
- PHX added connector heaters

Probability of being MPL Root cause: Medium High

So what WAS the root cause?

- We might never know
- No sign (so far) of the lander in any of the terabytes of HiRISE data suggests it might have broken up into smaller pieces during entry.
  - Or maybe, like Beagle2 it is on the surface perhaps covered in dust.

Lessons we can take from MPL

- EDL communication really does help allow us to go forward.
- The "onion" of complexity needs to be peeled all the way in.
  - You are rarely done testing or analyzing these when you think you are.
- Understand what it is you are flying.
  - Don't just put things together in haste and hope that it works.
  - Dive deep inside so that you know what's inside and can see for yourself that it will work.

Last words

- Remember, failure is the *default outcome* in everything we do.
- It takes intense perseverance and energy to force complex systems we build to work as we hope they will.